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Variations in air and ground temperature and the POM model: results from the Northern Hemisphere

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Abstract

The POM model for comparing air and ground temperatures is based on the assumption that surface air temperature (SAT) records provide a good prediction of climate induced thermal transients in the shallow subsurface of the Earth. I explore the sensitivity of this model to surface forcings at time scales appropriate for climate reconstructions. I find that the misfit is sensitive to periods longer than about 20 years, is a maximum when the period and the length of the time series are equivalent and then decreases for longer periods. The pre-observation mean (POM) is relatively insensitive to periods equal to the length of the time series. Sensitivity increases for periods greater than the length of the forcing time series. The POM is significant as long as air and ground temperatures faithfully track each other, and these tests provide a method for assessing this assumption. The sensitivity of comparisons between the average Northern Hemisphere gridded SAT record and subsurface temperature depth-profile as a function of forcing period is assessed. This analysis indicates that the average SAT and reduced temperature-depth profile is in good agreement. Some improvement in misfit can be made by decreasing the amplitude of the forcing function at intermediate periods but this effect has negligible influence on the POM. Thus, the joint analysis of borehole temperatures and SAT records indicate warming of about 1.1°C over the last 500 years, consistent with previous studies.

1 Introduction

Analysis of present-day borehole temperature-depth profiles for ground surface temperature (GST) histories is an important source of climate change information (e.g., Pollack and Huang, 2000). Conductive temperature-depth profiles reflect the linear combination of two diffusive processes, the upward flow of heat from the Earth's interior and the changing temperature at the Earth's surface. The former process is manifest as a systematic increase in temperature with depth, reflecting the flow of heat from the Earth's deep interior toward the surface. At the time scale of climate studies, this gradient together with the thermophysical rock properties form the background thermal regime against which anomalies can be referenced. The later process, changing surface temperature with time leads to curvature at depth in the shallow subsurface. The coefficient of thermal diffusivity (1×10^{-6} m^2/s) links depth and time so that temperature as a function of depth can be transformed to temperature as a function of time. Theoretically GST histories can be reconstructed anywhere subsurface heat transfer is conductive and constitute an important dataset in areas where other sources of paleoclimatic information is limited (e.g., Lachenbruch and Marshall, 1986; Taylor et al., 2006).

Borehole temperature climate analysis is powerful because it is rooted in the physics of heat diffusion and does not suffer from ambiguities due to an empirical calibration between a proxy measurement and temperature. The magnitudes of temperature variations are well resolved but like any diffusive process the resolution of individual events is a function of frequency (e.g., Clow, 1992; Beltrami and Mareschal, 1995; Harris and Chapman, 1998a). The subsurface diffusion of temperature caused by a periodic surface temperature condition can be described by (e.g., Carslaw and Jaegar, 1959),

$$T(z,t) = T_o + \Delta T \exp\left(-z\sqrt{\frac{f\pi}{\alpha}}\right)\cos\left(2\pi f t - z\sqrt{\frac{f\pi}{\alpha}}\right) \quad (1)$$

where T is temperature, T_o is the mean surface temperature, ΔT is the amplitude of the surface variation, f is the frequency of the surface wave and α is thermal diffusivity. The exponential term describes the attenuation of a thermal perturbation with depth and shows that the attenuation is proportional to the frequency. High frequency climatic information is lost at relatively shallow depths, while low frequency climatic information penetrates to greater depth (Fig. 1). For example, if we assume that the fractional change in surface temperature we can resolve is 0.01, a periodic surface temperature variation with a 10-year period and a 1°C amplitude is limited to depths less than 50 m, while a 50-year period oscillation is limited to depths less than 100 m. The loss of frequency content with depth translates to a loss of temporal resolution with time in the past because high frequency information has been attenuated. Thus analysis of temperature depth profiles for climatic change is ideally suited for determining long-term (centennial scale) trends of surface temperature change.

Most temperature-depth profiles are located in areas where surface air temperature (SAT) records exist and the combination of these datasets offer additional information about our climate system. Comparisons of these datasets, either qualitatively (Huang et al., 2000) or quantitatively (Harris and Chapman, 2001) increases the utility of GST reconstructions by providing independent evidence of the past 150 years of temperature change (the period of overlap), and by helping to place SAT records in a longer context. Long-term regional comparisons at the 100-year time scale generally show good agreement between air and ground temperatures (Huang et al., 2000; Harris and Chapman, 2001; Beltrami, 2002; Pollack and Smerdon, 2004). Modeling studies using General Circulation Models allow comparisons between air and ground temperatures at longer time scales and also suggest good agreement between changes in air and ground temperature (Gonzáles-Rouco et al., 2003, 2006). However, questions regarding changes in the relationship between air and ground temperatures have prompted detailed investigations often in combination with other meteorological parameters (e.g. Baker and Ruschy, 1993; Putnam and Chapman, 1996; Smerdon et al., 2003, 2004, 2006; Bartlett et al., 2006; Chudinova et al., 2006). These studies have found that, over the time period of study, variations in air and ground temperatures generally track each other. More importantly however, these studies illuminate processes that may adversely influence the relationship between air and ground temperatures. These processes include trends associated with cold season snow cover and warm season solar insolation. Additionally, other processes such as changing ground cover and soil moisture has also been suggested to adversely affect the relationship between air and ground temperature (Lewis and Wang, 1998; Nitoui and Beltrami, 2005; Pollack et al., 2005; Mottaghy and Rath, 2005). Unfortunately, regional networks documenting these processes are not long enough to unambiguously address this issue at time scales appropriate for borehole climatic studies. While notable exceptions at specific locations exist (e.g., Baker and Baker, 2002; Bartlett et al., 2006; García-Suárez and Butler, 2006), most studies documenting variations between air and ground temperatures are at the annual time scale or are over a few annual cycles, and in the context of GST reconstructions, these high frequencies are attuneated before they can reach depths relevant for centennial scale GST reconstruction histories.

The assumption that air and ground temperatures track each other has specifically been called into question because paleoclimatic studies using temperature-depth profiles estimate greater warming than early studies relying on some networks of proxy data (Harris and Chapman, 2001). Borehole studies of the Northern Hemisphere of climate change have generally inferred about 1°C of total warming over the past 500 years (Huang et al., 2000; Harris and Chapman, 2001; Beltrami, 2002; Beltrami and Bourlon, 2004), whereas many multiproxy networks of climate change generally indicate less total warming over this same time period (e.g., Jones et al., 1988; Mann et al., 1999; Crowley and Lowery, 2000; Briffa et al., 2001). These multiproxy networks rely to a large extent on tree rings, which are mostly sensitive to warm season conditions when the trees are most active (Briffa et al., 2001). In contrast subsurface temperatures are sensitive to the annual signal of surface temperature at the centennial time scale. Because much of the warming over the past 150 years has taken place during the cold season (Jones and Moberg, 2003), Harris and Chapman (2005) argued that warming estimates derived from the two datasets could be reconciled by recognizing that subsurface temperatures capture annual warming trends while tree-rings may only be capturing warm season trends. Tree-ring networks processed to retain low frequency information are in general agreement with borehole temperature profiles (Esper et al., 2002; Moberg et al., 2005). However the question of long-term tracking between air and ground temperatures remains an open question. Does the relationship between air and ground temperatures change significantly at scales appropriate for long-term climatic studies? If the change in the relationship between air and ground temperatures is large, can it reconcile warming estimates derived from borehole and multiproxy data? This study explores these questions with a series of numerical tests and then with data from the Northern Hemisphere. The purpose of this study is to explore the sensitivity of quantitative comparisons between SAT records and borehole temperature profiles as a function of frequency.

2 The POM model

In a series of papers Harris and Chapman (1998b, 2001, 2005) argued that a good way to quantitatively compare air and ground temperatures at long time scales is to compute a transient temperature profile using the SAT record as a forcing function at the Earth's surface. In this model, the SAT record is parameterized as a series of annual mean temperatures, T_i, corresponding to time before the temperature-depth measurements were made, τ_i. The transient temperature profile, $\Delta T_t(z)$ can be expressed as (Carslaw and Jaegar, 1959),

$$\Delta T_t(z) = (\mathrm{POM} - T_1) erfc\left(\frac{z}{\sqrt{4\alpha\tau_1}}\right) + \sum_{i=2}^{N} \Delta T_i erfc\left(\frac{z}{\sqrt{4\alpha\tau_i}}\right) \quad (2)$$

where POM is the initial condition termed the pre-observational mean, α is the thermal diffusivity, and erfc is the complementary error function. This equation contains two free parameters, the POM and α, and N fixed SAT values. In practice the value of α is usually assumed based on laboratory measurements that indicate a value of 1×10^{-6} m^2/s is a good average value (Clauser and Huenges, 1995), and the POM is selected as the value that minimizes the misfit between the reduced temperature profile and transient temperature profile. The algorithm determines the optimum POM that minimizes the least squares misfit function,

$$S(m)^2 = \sum_{z=0}^{2tl} (\Delta T_r - \Delta T_t)^2 \quad (3)$$

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where ΔT_r is the reduced temperature profile relative to the surface temperature intercept, ΔT_t is the transient profile relative to the POM, and 2tl is twice the thermal length based on the first annual SAT value. Limiting the misfit to a depth of two thermal lengths increases the sensitivity of the misfit by restricting the calculation to the shallow subsurface where sensitivity to surface temperature forcing is the greatest. Below this depth there is relatively little signal generated from the SAT time series. The POM has significance to the extent that air and ground temperatures faithfully track each other.

In addition to representing a temperature history, the reduced temperature profile and SAT records are also a measure of the change in heat, ΔQ (e.g., Beltrami et al., 2002), where

$$\Delta Q = mc\Delta T \tag{4}$$

m is mass and c is specific heat. These changes in heat content are both relative to a reference temperature, the surface temperature intercept for the reduced temperature profile, and the POM for the SAT record. In this framework, the algorithm adjusts the POM, until the two quantities of heat are in agreement to the extent possible with a single parameter, and in the least squares sense. The magnitude of the least squares misfit gives a measure of how well the temperature histories agree. That is, while we may have the same quantity of heat in the atmosphere and ground, if the temperature history is different, then the least squares misfit may be large and the diffusion model may not be valid.

Advantages of the POM model are multi-fold (Harris and Chapman, 1998b). First, this model allows a quantitative comparison between SAT records and reduced temperature profiles using the same frequency-depth dependence. Comparisons between GST inverse solutions and SAT records only provide a qualitative comparison that may be misleading because of the different frequency content of the two records being compared. Additionally because this formulation solves the heat equation in the forward sense it is very stable, and finally it minimizes the number of free parameters. In this sense it is a simple model that reproduces the reduced temperature profile without over parameterizing the solution. In fact, generally good fits are obtained with a single POM (e.g. Harris and Chapman, 2001).

Ground surface temperature history solutions fitting the reduced temperature profile are not unique. Large misfits may be indicative of 1) significant non-diffusive heat transfer so that a purely diffusive model is inappropriate; 2) a significantly changing relationship between air and ground temperatures; and 3) a significant thermal event prior to the start of the SAT time series. If a significant thermal event prior to the start of the SAT time series is suspected, adding additional parameters which might take the form of step changes in temperature may be warranted (e.g., Harris and Gosnold, 1999). Conceptually, this approach assumes that we know approximately the past 150 years of temperature change from the SAT record and that the relationship between air and ground temperature has not changed significantly. The SAT record fits that portion of the reduced temperature profile and the remaining misfit is modeled in terms of one (the POM) or more step functions. In the sensitivity study that follows I focus on the relationship between air and ground temperatures through time.

3 Sensitivity of the POM model to surface temperature forcing

With increasing attention being paid to the relationship between air and ground temperatures it is worthwhile investigating the sensitivity of the POM model to potential discrepancies in the frequency content of the surface forcing function and the reduced temperature profile. Discrepancies in the frequency content of these two signals might arise from some process that distorts the SAT signal as it enters and diffuses through the subsurface. To explore this issue I investigate a number of synthetic tests. In essence each test consists of constructing a true surface forcing and diffusing it into the subsurface to produce a true transient temperature profile. The surface forcing is then distorted in amplitude or phase or both for a particular period, and the POM that produces the minimum misfit between the true and synthetic temperature profile is determined. This test provides an indication of the sensitivity of the root mean square

(RMS) misfit, and the POM, to a particular forcing period.

In the first set of synthetic tests, I construct a surface forcing function having a duration of 144 years and consisting of 72, 144, and 500 year periods, each with an amplitude of 0.2°C (Fig. 2a). To investigate the impact of a subsurface process muting a particular frequency, three transient temperature profiles are constructed each with either the 72, 144, or 500 year period missing (Fig. 2b). In constructing each of these transients the POM is 0°C. Because a particular frequency is muted for each transient, the subsurface heat content is less than that constructed using all periods (black line, Fig. 2b), as indicated by the smaller area under the curve. The surface forcing containing all periods is diffused into the subsurface and the RMS misfit is calculated as a function of the POM for each transient (Fig. 2c). This set of simulations demonstrates several important features of the POM model. In each case the minimum RMS misfit corresponds to a POM shifted toward a positive value, relative to the true value of 0°C. The shift in POM decreases the effective heat content of the surface forcing to match the subsurface heat content of the muted transients. Note however that the change in POM from the true value is less than 0.2°C. The second feature is the danger of taking a model fit as evidence of faithful tracking between air and ground temperatures. For each comparison the minimum RMS misfit is less than 40 mK. In this set of simulations the RMS misfit is calculated between z=0 and 270 m (two thermal lengths for a 144 year times series). In these tests, the sensitivity of the misfit function is a maximum because the misfit is calculated to the surface where there has been no attenuation of the surface forcing. In practice reduced temperature profiles rarely start at the surface and because of the frequency dependence of diffusion the sensitivity to the misfit function is decreased.

In reality, the subsurface process distorting the surface forcing may not entirely mute a specific frequency and may also affect the phase. Can the POM model be used to investigate tracking between air and ground temperatures at specific frequencies? I investigate two aspects of this question with a series of synthetic tests that extends the analysis shown in Fig. 2. The first aspect is the sensitivity of the model misfit to changes in the amplitude and phase of a particular frequency. What frequencies is the model fit sensitive to and what frequencies are attenuated before having an influence on the model fit? The second aspect is the sensitivity of the POM to changes in the amplitude and phase of the forcing function.

In the second set of synthetic tests the true surface forcing contains periods of 18, 36, 72, 144, and 500 years, each with an amplitude of 0.2°C and phase shifted to produce recent warming of 1°C (black line, Fig. 3a). The forcing function has a duration of 144 years, and the true POM is 0°C. The resulting true synthetic temperature profile (black line, Fig. 3b) has an amplitude at the surface of 1°C. Synthetic transients are constructed by varying the amplitude and phase of the 144-year period, diffusing it into the subsurface, and determining the POM that minimizes the RMS misfit function. For the 144-year period the minimum RMS corresponds to an amplitude of 0.2°C, a phase of zero (Fig. 3c), and a POM of 0°C (Fig. 3d), as expected. More generally, Figs. 3c and d show how the POM and RMS misfit vary as a function of errant amplitudes and phases associated with the 144-year period. As an example, the amplitude of the 144-year period is increased to 1°C (red line, Fig. 3a). The synthetic forcing is diffused into the subsurface and the POM that minimizes the misfit shifts to a more positive value so that the effective heat content of the synthetic transient best matches the true transient in the least squares sense (Fig. 3b). For this example, the best fitting POM is 0.37°C and the misfit is relatively large at 121 mK. Figure 3c shows that the RMS misfit is generally more sensitive to the amplitude than the phase, although sensitivity to the amplitude is lost when the forcing is approximately $\pi/2$ out of phase. This loss of resolution occurs because this phase shift puts the misfit deeper in the subsurface and the effects of attenuation decrease the sensitivity to the misfit function.

In practice reduced temperature profiles do not start at the surface and contain noise. Both of these attributes influence the sensitivity of the RMS misfit and POM (Fig. 4). For comparison with later results, Figs. 4a and b repeats the simulations shown in Fig. 3. In the second set of simulations the reduced temperature profile corresponds to depths between 30 and 500 m (Figs. 4c and d). This decreases the sensitivity to the

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RMS misfit because of progressive amplitude attenuation with depth and indicates the importance of shallow data for comparisons between subsurface temperature profiles and SAT records. Finally 10 mK zero mean Gaussian noise is added which decreases the sensitivity of the RMS misfit function (Figs. 4e and f). This true reduced temperature profile has measurement characteristics similar to that for the Northern Hemisphere (Harris and Chapman, 2001). The decrease in RMS sensitivity is consistent with other studies showing the deleterious effects of measurement noise (e.g., Clow, 1992).

Figure 5 shows the RMS misfit and POM sensitivity for all periods contained in the true surface forcing function (Fig. 3). The reduced temperature profile extends between depths of 30 and 500 m, with a measurement spacing of 5 m to match the characteristics of the reduced temperature profile constructed for the Northern Hemisphere (Harris and Chapman, 2001). The sensitivity of the RMS misfit function increases with increasing period up to the duration of the time series (Fig. 5a). This is due to the frequency filtering coupled with the way the RMS is calculated. High frequency perturbations are filtered out before they can have a significant effect on the transient temperature profile and RMS misfit, no matter how big the amplitude. For the simulations shown here, the RMS is relatively insensitive to periods of 18 and 36 years, and relatively sensitive to periods of 72 and 144 years. The 500-year period adds a long period increase in the forcing function but the RMS misfit has decreased sensitivity because of decreased structure in the synthetic temperature profile which can be well fit by shifting the POM. In contrast, the 144-year period provides the most structure. As the amplitude increases the RMS increases because more structure is added to the synthetic profile. As the sensitivity to the RMS misfit increases with increasing period, so too does the sensitivity of the POM (Fig. 5b). However, even for an errant period of 144 years with an amplitude of 1°C the error in POM is only 0.05°C. In contrast the POM is much more sensitive to the 500-year period where an errant amplitude of 1°C would produce an errant POM of 0.8°C. These results indicate that very low frequency mismatches between the forcing function and reduced temperature profile have the potential to produce misleading results.

4 Data

To investigate tracking between the average Northern Hemisphere temperature-depth profile and SAT record at various frequencies, I focus on the Northern Hemisphere where most of the temperature-depth profiles exist (Fig. 6a). Temperature-depth profiles come from the global database for climate change studies (Huang and Pollack, 1998). Attributes of temperature profiles included in the database are described in Pollack and Huang (2000). These attributes include temperature measurements at least as shallow as 100 m and at least as deep as 200 m. Additionally the temperature data require a smooth variation with depth and be free of evidence of advective disturbances or permafrost.

Gridded SAT data (Jones and Moberg, 2003) from grid cells that contain temperature profiles are weighted and averaged together. The data cover a time period between 1856 and 2001. A linear fit to the average SAT record computed is this way warms by 0.8°C over the past 145 years (Fig. 6b).

Temperature-depth profiles are analyzed as described in Harris and Chapman (2001, 2005). For each temperature profile, the background thermal field is parameterized in terms of the long-term thermal gradient and mean surface temperature intercept to form the background thermal regime. For consistency these background parameters are estimated for each profile using data below 160 m, a depth dictated in part by the data, but also sufficient to minimize perturbations from recent GST variations, while also providing a sufficient depth interval to obtain a robust estimate of these parameters. The background thermal regime is subtracted from each temperature-depth profile to form a reduced temperature profile. This compilation of temperature profiles represents data collected over a 44-year period (1958–2001). These profiles are forward continued in time using a Laplace transform, assuming a constant GST between the year the borehole was logged and 2001 (Harris and Chapman, 2001). This procedure yields conservative and consistent reduced temperature profiles. An average reduced temperature profile is computed by averaging individual reduced temperatures for each 5°×5° grid cell containing temperature logs, weighting each grid cell by its area, and then averaging all grid cells together. The mean reduced temperature profile (Fig. 6c) has a magnitude of 0.5°C at 30 m that extrapolates to an amplitude of 0.8°C at the surface. This profile represents the diffused GST history at the Earth's surface over the past several centuries. A simple two parameter inversion that reproduces the average reduced temperature profile is a linear increase in temperature of 0.8°C over the last 160 years, in excellent agreement with the linear trend fit to the averaged SAT record.

5 Northern Hemisphere air and ground temperature tracking

The Northern Hemisphere SAT record is diffused into the subsurface using Eq. (2). Figure 6c shows a comparison between the reduced temperature profile and the best fitting transient temperature profile. The best fitting model jointly fitting the SAT and reduced temperature profile yields a POM of 0.58°C below the 1961–1990 mean SAT and a thermal diffusivity of 1×10^{-6} m^2/s. The combination of this POM with the last 145 years of SAT data yield a transient profile that is an excellent fit to the observations with a RMS misfit of 18 mK (Fig. 6d). The POM model is very sensitive to the POM whereas it is relatively insensitive to the choice of thermal diffusivity. Part of the explanation is that the quantity of heat in the ground does not depend on either the thermal diffusivity or the timing of individual events (Eq. 4). These results are similar to those of Harris and Chapman (2001), albeit for a larger data set of temperature depth profiles in this study.

The numerical tests described above suggest a method for investigating tracking at periods longer than are commonly available at climate observatories. The spectrum of the Northern Hemisphere SAT record collocated with boreholes shows power for periods greater than about 20 years (Fig. 7). The amplitudes associated with these periods are summarized in Table 1. Sensitivity of the POM model for these periods is investigated by varying the amplitude of each period and adding it to the average SAT record. Here, I assume that the phase between air and ground temperatures is not

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changed. The synthetic SAT is then used as a forcing function at the Earth's surface to compute a transient profile that is compared against the average reduced temperature profile. There is very little sensitivity to periods of 20 years and less as indicated by the RMS misfit plot (Fig. 6). However, there is good sensitivity the longer periods investigated as the RMS misfit shows well-defined minima. For the periods of 36, 48 and 72 years, the difference in RMS misfit between the observed and optimum amplitude is relatively large (Table 1). It is worth noting that in all cases the minimum RMS misfit is obtained by decreasing the observed amplitude. This result suggests that some process is decoupling air and ground temperatures in such a way as to mute overall warming diffusing into the ground. However, for these periods and changes in RMS misfit, changes to the POM are negligible. Thus, even though we can achieve a smaller RMS misfit by decreasing the amplitude associated with these periods, the overall impact on the POM, and therefore overall warming remains unchanged. Thus decoupling of air and ground temperatures at timescales appropriate for long-term climatic studies do not appear significant for the POM model.

While this modeling cannot determine a particular process that is decoupling air and ground temperatures it is interesting to note that these results are consistent with the impact of snow cover in North America (Bartlett et al., 2005). In this scenario, part of cold season warming signal is attenuated as it passes through the snow cover and does not reach the ground. As noted above though, this effect is small at these periods. Bartlett et al. (2005) also concluded that the impact of snow cover on air and ground temperatures is small. These results suggest that the discrepancy between warming estimates derived from borehole temperature records and multiproxy networks are unlikely to be reconciled by appealing to a process decoupling air and ground temperatures.

6 Conclusions

On the basis of this analysis I conclude the following:

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1. High frequency components of GST variations are diffused out of the system at relatively shallow depths. Reduced temperature profiles starting at 20 m, or deeper are relatively insensitive to periods shorter than about 25 years.

2. Sensitivity of the RMS misfit and the POM increase as the period of forcing increases up to the time span of the forcing function.

3. The Northern Hemisphere extratropical average reduced temperature profile compares well with an average SAT record constructed from collocated 5°×5× grid cells. The POM is –0.7°C below the 1961–1990 mean SAT and the RMS misfit is 18 mK.

4. The POM model uses two free parameters and is very sensitive to the initial condition, the POM. This model is relatively insensitive to the choice of thermal diffusivity. Thermal diffusivity enters the model in the same way that time does, and because diffusion is relatively insensitive to time, this model is also relatively insensitive to the thermal diffusivity.

5. Long-term changes between air and ground temperature changes may be present. These changes tend to mute SAT warming as observed in the ground, and are consistent with the effect of snow muting cold season warming. This effect has a negligible influence on the POM.

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References

Baker, J. M. and Baker, D. G.: Long-term heat flux and heat storage at a mid-latitude site, Clim. Change, 54, 295–303, 2002.

Baker, D. G. and Ruschy, D. L.: The recent warming in Eastern Minnesota shown by ground temperatures, Geophys. Res. Lett., 23, 371–374, 1993.

Bartlett, M. G., Chapman, D. S., and Harris, R. N.: Snow effect on North American ground temperatures, 1950–2002, J. Geophys. Res., 110, F03008, doi:10.1029/2005JF000293, 2005.
Bartlett, M. G., Chapman, D. S., and Harris, R. N.: A decade of ground-air temperature tracking at Emigrant Pass Observatory, Utah, J. Climate, 19, 3722–3731, 2006.
Beltrami, H: Climate from borehole data: Energy fluxes and temperatures since 1500, Geophys. Res. Lett., 29, 2111, doi:10.1029/2002GL015702, 2002.
Beltrami, H. and Bourlon, E.: Ground warming patterns in the northern hemisphere during the last five centuries, Earth Planet. Sci. Lett., 227, 169–177, 2004.
Beltrami, H. and Mareschal, J. C.: Resolution of Ground Temperature Histories Inverted from Borehole Temperature Data, Global Planet. Change, 11, 57–70, 1995.
Beltrami, H., Smerdon, J., Pollack, H. N., and Huang, S.: Continental heat gain in the global climate system, Geophys. Res. Lett., 29, 1167, doi:10.1029/2001GL014310, 2002.
Briffa, K. R., Osborn, T. J., Schweingruber, F. H., Harris, I. C., Jones, P. D., Shiyatov, S. G., and Vaganov, E. A.: Low frequency temperature variations from a northern tree-ring density network, J. Geophys. Res., 106, 2929–2941, 2001.
Carslaw H. S. and Jaeger J. C.: Conduction of Heat in Solids. Oxford, UK: Oxford Univ. Press. 510 pp. 2nd ed., 1959.
Chudninova, S. M., Frauenfeld, O. W., Barry, R. G., Zhang, T., and Sorokovikov, V. A.: Relationship between air and soil temperature trends and periodicities in the permafrost regions of Russia, J. Geophys. Res., 111, F02008, doi:10.1029/2005JF000342, 2006.
Clauser, C. and Huenges, E. L.: Thermal conductivity of rock and minerals, in: Rock Physics and Phase Relations: A Handbook of Physical Constants, Ref. Shelf Ser., vol 3, edited by: Ahrens, T. J., 105–126, Washington D. C., 2005.
Clow, G.: Temporal resolution of surface-temperature histories inferred from borehole temperature measurements, Global Planet. Change, 98, 81–86, 1992.
Crowley, T. J. and Lowery, T. S.: How warm was the Medieval warm period?, Ambio, 29, 51–54, 2002.
Esper, J., Cook, E. R., and Schweingruber, F. H.: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability, Science, 295, 2250–2253, 2002.
García-Suárez, A. M. and Butler, C. J.: Soil temperatures at Armagh Observatory, Northern Ireland, from 1904 to 2002, Int. J. Clim., 26, 1075–1089, 2006.
González-Rouco, J. F., Beltrami, H., Zorita, E., and von Storch, H.: Simulation and inversion of borehole temperature profiles in surrogate climates: Spatial distribution and surface cou-

pling, Geophys. Res. Lett., 33, L01703, doi:10.1029/2005GL024693, 2006.
Gonzalez-Rouco, J. F., von Storch, H., and Zorita E.: Deep soil temperature as proxy for surface air-temperature in a coupled model simulation of the last thousand years, Geophys. Res. Lett., 30, 2116–2119, 2003.
Harris, R. N. and Chapman, D. S.: Borehole temperatures and a baseline for 20th-century global warming estimates, Science, 275, 1618–1621, 1997.
Harris, R. N. and Chapman, D. S.: Geothermics and climate change: Part 1, Analysis of borehole temperatures with emphasis on resolving power, J. Geophys. Res, 103, 7363–7370, 1998a.
Harris, R. N. and Chapman, D. S.: Geothermics and climate change: Part 2, Joint analysis of borehole temperatures and meteorological data, J. Geophys. Res., 7371–7383, 1998b.
Harris, R. N. and Chapman, D. S.: Mid-Latitude (30°–60° N) climatic warming inferred by combining borehole temperatures with surface air temperatures, Geophys. Res. Lett., 28, 747–750, 2001.
Harris, R. N. and Chapman, D. S.: Borehole temperatures and tree-rings: Seasonality and estimates of extratropical Northern Hemispheric warming, J. Geophys. Res., F04003, doi:10.1029/2005JF000303, 2005.
Harris, R. N. and Gosnold, W. D.: Comparisons of borehole temperature-depth profiles and surface air temperatures in the northern plains of the U.S., Geophys. J. Int., 138, 541–548, 1999.
Huang, S. and Pollack, H. N.: Global Borehole Temperature Database for Climate Reconstruction (IGBP PAGES/Word Data Center-A for Paleoclimatology Data Contribution Series No. 1998-044, NOAA/NGDC Paleoclimatology Program Boulder, Colorado, 1998).
Huang, S., Pollack, H. N., and Shen, P. Y.: Temperature trends over the past five centuries reconstructed from borehole temperatures, Nature, 403, 756–758, 2000.
Jones, P. D., Briffa, K. R., Barnett, T. P., and Tett, S. F. B.: High-resolution palaeoclimatic records for the last millennium: interpretation, integration and comparison with General Circulation Model control-run temperatures, The Holocene, 8, 455–471, 1998.
Jones, P. D. and Moberg, A.: Hemispheric and large-scale surface air temperature variations: an extensive revision and an update to 2001, J. Climate, 16, 206–223, 2003.
Lachenbruch, A. H. and Marshall, B. V.: Changing climate; geothermal evidence from permafrost in the Alaskan Arctic, Science, 23, 689–696, 1986.
Lewis T. J. and Wang, K.: Geothermal evidence for deforestation induced warming: implications

for the climatic impact of land development, Geophys. Res. Lett., 25, 535–538, 1998.
Mann, M. E., Bradley, R. S., and Hughes, R. S.: Northern hemisphere temperatures during the past millennium: inferences, uncertainties and limitations, Geophys. Res. Lett., 26, 759–762, 1999.
Moberg, A., Sonechkin, D. M., Holmgren, K., Datsenko N. M., and Karlen, W.: Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data, Nature, 433, 613–1014 doi:10.1038/nature03265, 2005.
Mottaghy, D. and Rath, V.: Latent heat effects in subsurface heat transport modeling and their impact on palaeotemperature reconstructions, Geophys. J. Int., doi:10.1111/j.1365-246X.2005.02843.x, 2005.
Nitoiu, D. and Beltrami, H.: Subsurface thermal effects of land use changes, J. Geophys. Res., 110, F01005, doi:10.1029/2004JF000151, 2005.
Pollack, H. N. and Huang, S.: Climate reconstruction from subsurface temperatures, Ann. Rev. Earth Planetary Sci., 28, 339–365, 2000.
Pollack, H. N., Smerdon, J. E., and van Keken, P. E.: Variable seasonal coupling between air and ground temperatures: A simple representation in terms of subsurface thermal diffusivity, Geophys. Res. Lett., 32, L15405, doi:10.1029/2005GL023869, 2005.
Pollack, H. N. and Smerdon, J. E.: Borehole climate reconstructions: Spatial structure and hemispheric averages, J. Geophys. Res., 109, D11106, doi:10.1029/2003JD004163, 2004.
Putnam S. N. and Chapman, D. S.: A geothermal climate-change observatory: first year results from Emigrant Pass Observatory in northwest Utah, J. Geophys. Res. 101, 21 877–21 890, 1996.
Smerdon, J. E., Pollack, H. N., Cermak, V., Enz, J. W., Kresl, M., Safanda, J., and Wehmiller, J. F.: Air-ground temperature coupling and subsurface propagation of annual temperature signals, J. Geophys. Res., 109, D21107, doi:10.1029/2004JD005056, 2004.
Smerdon, J. E., Pollack, H. N., Enz, J. W., and Lewis, M. J.: Conduction-dominated heat transport of the annual temperature signal in soil, J. Geophys. Res., 108(B9), 2431, doi:10.1029/2002JB002351, 2003.
Smerdon, J. E., Pollack, H. N., Cermak, V., Enz, J. W., Kresl, M., Safanda, J., and Wehmiller, J. F.: Daily, seasonal and annual relationships between air and subsurface temperatures. J. Geophys. Res., 111, D07101, doi:10.1029/2004JD005578, 2006.
Taylor, A. E., Wang, K., Smith, S. L., Burgess, M. M., and Judge A. S.: Canadian Arctic Permafrost Observatories: Detecting contemporary climate change through inversion of subsur-

face temperature time series, J. Geophys. Res., 111, B02411, doi:10.1029/2004JB003208, 2006.
Turcotte, D. L. and Schubert, G.: Geodynamics, Cambridge Univ. Press, New York, 456 p., 2002.

Table 1. Optimum power for POM model.

Period yr	Observed Amplitude °C	Optimum Amplitude °C	ΔRMS °C	ΔPOM °C
18	0.06	–1.10	0.003	0
36	0.07	–0.50	0.009	0.016
48	0.16	–0.20	0.018	0.016
72	0.17	–0.20	0	0
144	0.28	0.20	0.037	0.016
500	–	–0.20	0.003	0.218

ΔRMS is the change in root mean square misfit between the observed and optimum amplitude.
ΔPOM is the change in pre-observational mean between the observed and optimum amplitude.

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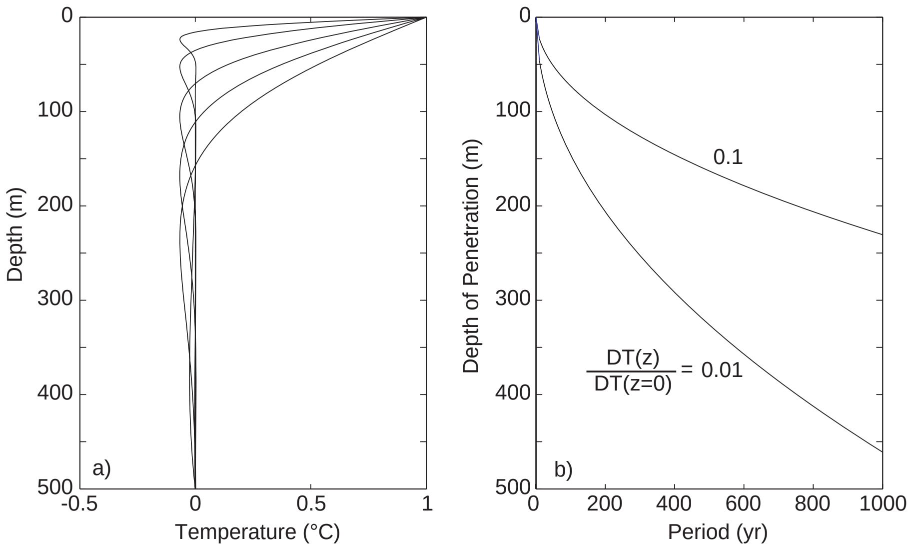

Fig. 1. The frequency dependence of diffusion. **(a)** Transient temperature profiles constructed from forcing functions with periods of 5, 10, 50, 100, 200, and 500 years. In each case the forcing function has an amplitude of 1°C and is phase shifted to reflect recent warming. **(b)** Depth attenuation as a function of period. The lines show the depth at which the ratio of the subsurface temperature perturbation to the surface amplitude are lost in the background.

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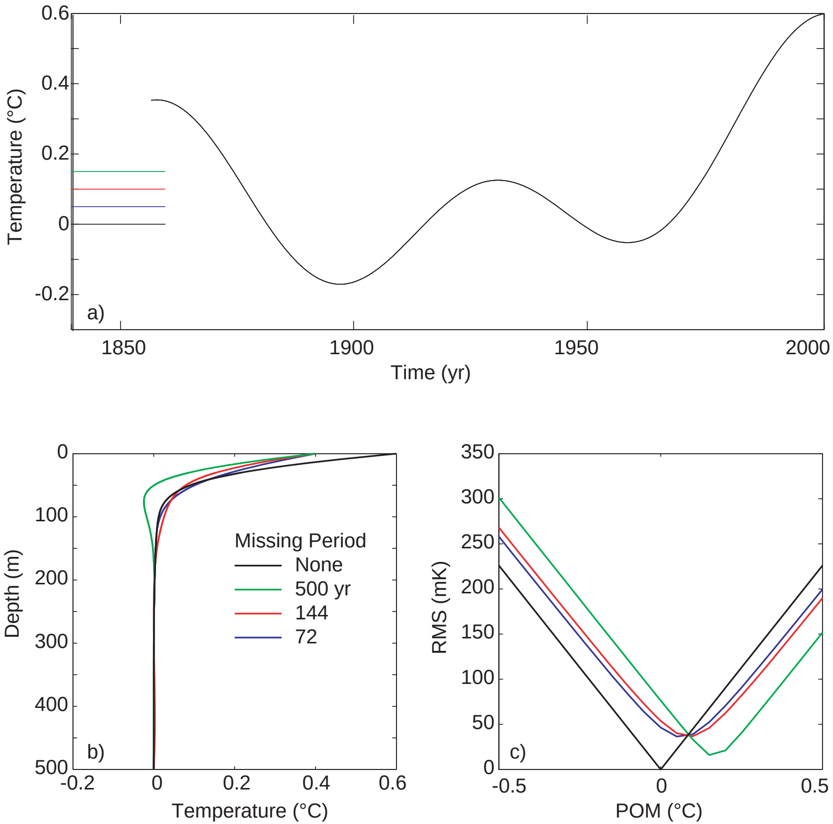

Fig. 2. Sensitivity of the POM model to a missing frequency. **(a)** True surface forcing function composed of a linear combination of surface forcings, each with an amplitude of 0.2°C and periods of 72, 144, and 500 years. The forcings have been phase shifted to show recent warming of 0.6°C. **(b)** Transient temperature profiles constructed from surface forcing (black) and with individual periods muted. **(c)** RMS misfit as a function of POM for each comparison.

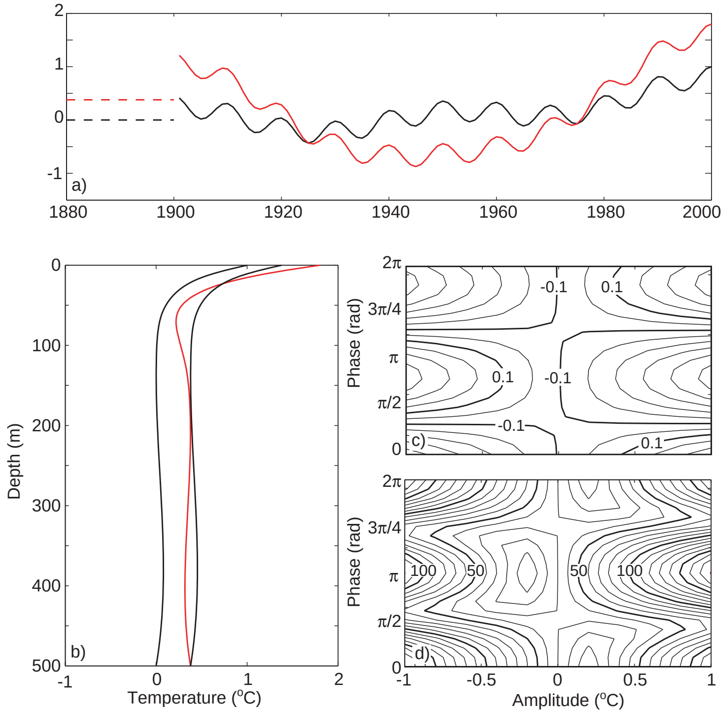

Fig. 3. Sensitivity of the POM model as a function of forcing function amplitude and phase for the 144 year period. **(a)** True surface forcing function (black line) composed of a linear combination of waves, each with an amplitude of 0.2°C and periods of 18, 36, 72, 144, and 500 years. The forcings have been phase shifted to show recent warming of 1.0°C. Dashed lines show POM. Red and blue lines show example surface forcing where the amplitude of the 144 year period has been increased to 1.0° and –1.0°C, respectively. **(b)** Transient temperature profiles constructed from surface forcing (black) and example forcings (red and blue lines). These profiles are offset by their respective POMs. **(c)** POM as a function of the amplitude and phase of the 144 year period. The contour interval is 0.1°C. (b) RMS misfit as a function of amplitude and phase of the 144 year period. The contour interval is 10 mK.

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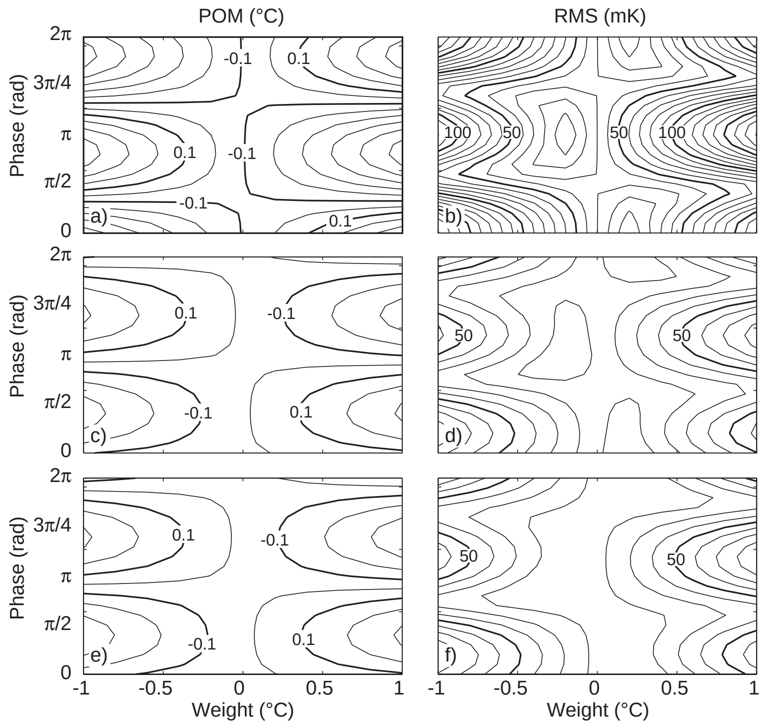

Fig. 4. Left column shows best fitting POM as a function of forcing function amplitude and phase with a contour interval of 0.1°C. Right column shows root mean square misfit between true and synthetic model as a function of forcing function amplitude and phase with a contour interval of 10 mK. The forcing function has a period and duration of 100 years. **(a)** and **(b)** True reduced temperature profile consists of temperature data from 0 to 500 m with a spacing of 1 m. Noise free. **(c)** and **(d)** True reduced temperature profile consists of temperature data from 30 to 500 m with a spacing of 1 m. Noise free. **(e)** and **(f)** True reduced temperature profile consists of temperature data from 30 to 500 m depth, a measurement spacing of 5 m. 10 mK zero-mean Gaussian noise is added.

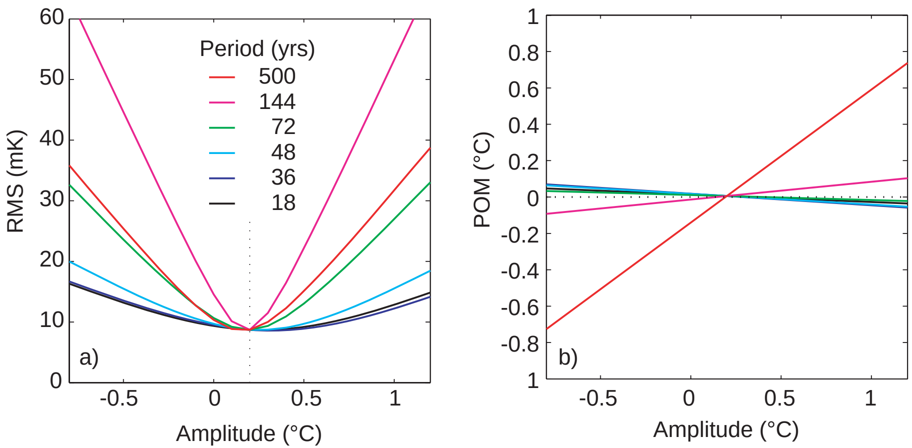

Fig. 5. Synthetic model results as a function of forcing function amplitude and period. Root mean square misfit and POM as a function of forcing function period and amplitude. In each case the duration of the forcing function is 100 years and the phase is adjusted to show recent warming. **(a)** POM. **(b)** Root mean square misfit.

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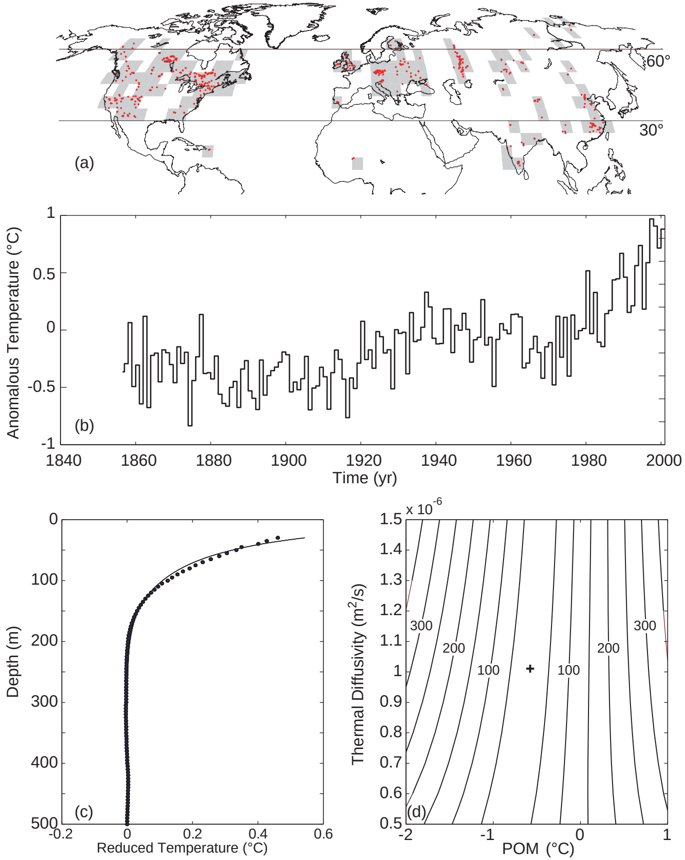

Fig. 6. Extratropical Northern Hemisphere surface air temperature record and average reduced temperature profile. **(a)** Location map showing boreholes (red circles) and gridded surface air temperature data. **b)** Average SAT record relative to 1961–1990 mean temperature. **(c)** Average extratropical reduced temperature profile (circles) and best fitting model based on POM and SAT record. **(d)** Sensitivity of model fit to the POM and thermal diffusivity.

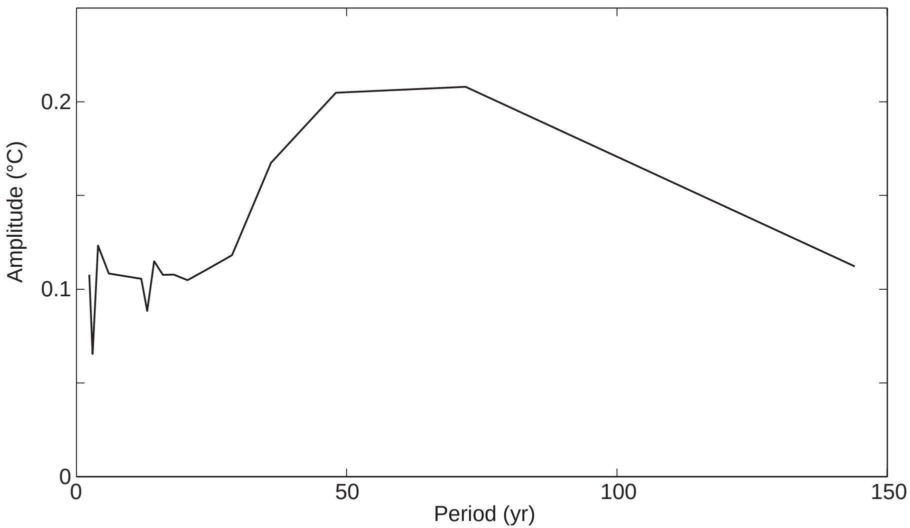

Fig. 7. Spectral analysis of Northern Hemisphere surface air temperature shown in Fig. 6. Most of the power is at between periods of 48 and 72 years.

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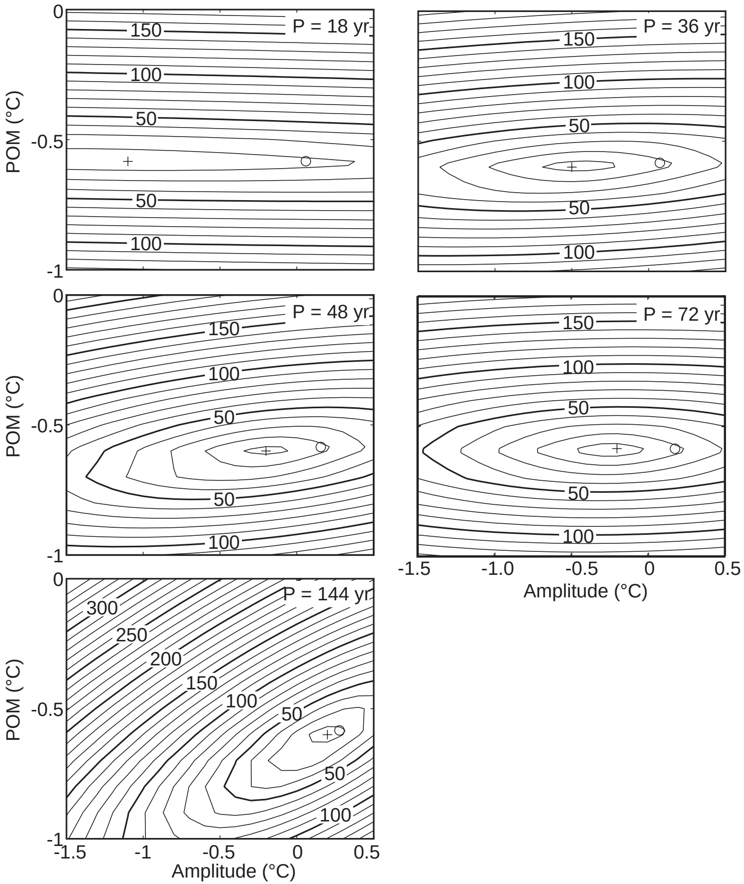

Fig. 8. RMS misfit as a function of forcing amplitude and pom for different forcing periods. Open circles show observed amplitude and crosses shown optimum amplitude (Table 1). Contour interval is 10 mK. Period, P, corresponding to each panel is shown in upper right corner. Sensitivity of the forcing period for the extratropical Northern Hemisphere.